

Properties of structural panels fabricated from bioremediated CCA-treated wood: Pilot scale

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Abstract

Particleboard and flakeboard panels were fabricated from remediated CCA-treated southern yellow pine. Treated wood, flaked or comminuted into particles, was remediated in 12-kg batches using oxalic acid extraction, followed by bioleaching with the metal-tolerant bacterium *Bacillus licheniformis*. Remediation resulted in removal of 80 percent Cu, 71 percent Cr, and 89 percent As for the particulate material and 83 percent Cu, 86 percent Cr, and 95 percent As for the flaked material. Particleboard and flakeboard panels were evaluated for modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond (IB) strength. Particleboard made from remediated material with 10 percent urea-formaldehyde resin showed an 18 percent reduction in MOE, 47 percent reduction in MOR, and 37 percent reduction in IB strength compared to comparable panels made from untreated wood. Flakeboard prepared from remediated material with 5 percent phenol-formaldehyde resin showed insignificant differences in MOE and MOR, and a 16 percent increase in IB strength compared to panels consisting of untreated wood. Properties of remediated particleboard were significantly diminished compared to those of panels made with untreated wood. MOR and MOE of remediated flakeboard were comparable to that of untreated material, but IB strength was increased. Flake geometry and type of resin, as well as differences in surface area and metal removal between the two wood geometries, may all account for variations in panel properties.

Since the early 1970s, an estimated 60 billion board feet of wood treated with chromated copper arsenate (CCA) has been placed in service in the United States (Cooper 1994, Micklewright 1994). There is concern about the disposal of this material as it comes out of service. In an effort to divert this resource from landfills, novel approaches have been developed to remediate, recycle, or reuse CCA-treated wood (Kamdem and Munson 1996, Stephan et al. 1996, Leithoff and Peek 1997, Smith and Shiau 1997, Kazi and Cooper 1999, Clausen 2000a, Ribeiro et al. 2000).

Environmental sampling demonstrated that metal-tolerant bacteria could readily be isolated from research test sites where treated stakes were being evaluated for long-term efficacy of wood preservatives (Cole and Clausen 1997, Clausen 2000b). A number of isolates were obtained by sampling research test sites with presumed elevated levels of copper (Cu), chromium (Cr), and arsenic (As) (Clausen 2000a), based on their ability to thrive on selective medium containing 0.02 percent CCA-C. The effectiveness of an organism to remove metals was determined by exposing 1 g of CCA-C-treated

wood, ground to pass a 20 mesh (0.841-mm) screen (nominal preservative retention of 6.4 kg/m³), to 50 mL of nutrient broth inoculated with the test organism and incubating the mixture at 30°C for 7 days at 15.7 rad·s⁻¹ (150 rpm). Following incubation, the saw dust was collected, oven dried, digested, and analyzed for copper, chromium, and arsenic content by inductively coupled plasma emission spectrometry according to American Wood-Preservers' Association standard A-21 to 00 (AWPA 2003).

Ideally, one would create a consortium with several isolates that could collectively remove copper, chromium, and arsenic

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from treated wood. Attempts to develop such a consortium with the isolates failed as a result of the rapid replication time (21 min) for *Bacillus licheniformis*, leading to domination by this isolate in cultures of mixed bacteria. Therefore, *B. licheniformis* has been the only bacterium extensively studied for bioremediating CCA-treated wood since 1996, when it was first isolated at the Valley View Experimental Exposure Site of the USDA Forest Service, Forest Products Laboratory, near Madison, Wisconsin (Cole and Clausen 1997). In laboratory studies, growth conditions for *B. licheniformis* to optimally remove copper and arsenic from treated wood particles or chips were determined to range from 25° to 28°C and from 15.7 to 20.9 rad·s⁻¹ (150 to 200 rpm) for 7 to 10 days (Clausen and Smith 1998, Clausen 2000a). Under these conditions, the bacterium was able to consistently remove 93 percent Cu and 45 percent As, but it was unable to effectively remove significant quantities of chromium. *Bacillus licheniformis* could more effectively remediate particulate wood than chipped material, due to its increased surface area.

Acid extraction was evaluated as a precursor to bacterial fermentation in an effort to enhance total metal removal, particularly of chromium. The rationale for combining acid extraction with bacterial fermentation was threefold. First, previous studies indicated that oxalic acid production plays a critical role in initiation of the decay process by brown-rot fungi (Green et al. 1991). Second, copper induces rapid oxalic acid production by copper-tolerant brown-rot fungi and is believed to be instrumental in the ability of these organisms to decay wood treated with copper organics (Clausen and Green 2003). Third, oxalic acid extraction has been shown to be an effective means of chemically leaching copper, chromium, and arsenic from treated wood (Cooper 1993; Kim and Kim 1993; Stephan et al. 1993, 1996). Clausen and Smith (1998) determined that oxalic acid extraction as a precursor to bacterial fermentation resulted in removal of 90 percent Cu, 80 percent Cr, and 100 percent As from treated chips. Oxalic acid extraction was optimized at 0.8 percent acid for 18-hour exposure at 25°C and a wood to acid ratio of 1:100 (w/v) (Clausen 2004). The two-step remediation sequence was shown to be more effective than either oxalic acid extraction or bacterial fermentation alone. Reversing the sequence (bacterial fermentation before acid extraction) was also not as effective at removing copper, chromium, and arsenic from treated wood.

The objective of the study reported here was to fabricate particleboard and flakeboard panels from remediated untreated southern yellow pine and CCA-treated southern yellow pine and to evaluate the panels for modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond (IB) strength.

Materials and methods

Remediation of CCA-treated wood

Once conditions were optimized on a laboratory scale, the two-step bioremediation process was scaled-up to pilot scale (approximately tenfold increase) in a 150-L stainless steel recirculating tank. The remediation process is described in detail in Clausen and Kenealy (2004). In brief, this process was used to evaluate 12-kg batches of particulate (3 by 8 mm) and flaked (0.5-mm thick by 11-cm long by varying width) southern yellow pine (*Pinus* spp.) treated with CCA-C to a nominal retention of 6.4 kg/m³. Particulate wood was placed in a woven polypropylene filter fabric bag in the recirculating tank;

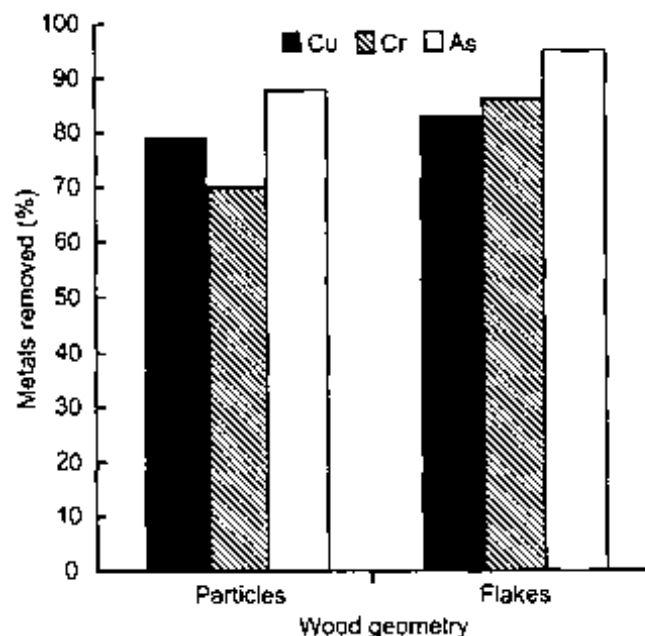


Figure 1. – Percentage of copper, chromium, and arsenic removed after 7 days of bioleaching with *Bacillus licheniformis*.

wood flakes were processed in a polypropylene mesh bag (Clausen and Kenealy 2004). Wood was exposed to 125 L of 0.8 percent oxalic acid, which was recirculated at 50 L/min and 27°C for 18 hours before the acid solution was exchanged with 125 L sterile nutrient broth. The pH was adjusted to 5.5 to 5.6 with NaOH before adding 1 L nutrient broth inoculum containing 6×10^7 colony forming units of *B. licheniformis* per mL. The inoculated broth was recirculated at 50 L/min at 27°C for 7 days. Samples of filtrate and bioremediated wood were analyzed for copper, chromium, and arsenic by inductively coupled plasma (ICP) according to AWP A-21-00 (AWPA 2003) (Clausen and Kenealy 2004). The final pH of the broth was 6.1 for the particles and 6.2 for the flaked material. Both particles and flakes were rinsed thoroughly with deionized water and air dried.

Panel fabrication

Panels were fabricated according to procedures outlined in the *Wood Handbook* (FPL 1999). The 61- by 61-cm- by 1.11-cm-thick panels (approximate specific gravity 0.65) were formed from untreated and remediated particles and untreated flakes; only two panels were formed from remediated flakes because of the amount of material available. For flakeboard panels, 2.5 kg untreated or remediated flakes were blended with 5 percent phenol-formaldehyde resin (#13S097, Dynea, Winnfield, LA). For particleboard panels, 2.5 kg untreated or remediated particles were blended with 10 percent urea-formaldehyde resin (#11A018, Dynea). Resin was applied in a rotating drum blender using an atomizing spray gun. Panels were hot-pressed in a 91.4- by 91.4-cm Nordberg press at 200°C using a PressMAN Press Control system (Alberta Research Center, Alberta, Canada). Panels were trimmed to 40.6 by 40.6 cm and cut into specimens for testing according to ASTM standard D 1037-96a (ASTM 1998). Specimens were conditioned for 2 weeks at 65 percent relative humidity and 20°C prior to testing.

Air sample analysis

During panel pressing, air samples were collected on mixed cellulose ester filters in a 1-m radius around the press. A total of 290 L was collected during pressing of remediated particleboard and 196 L during pressing of remediated flakeboard at a flow rate of 2.0 L/min. Samples were digested and analyzed by inductively coupled argon plasma atomic emission spectrometry for elemental arsenic vapors by the Wisconsin State Laboratory of Hygiene, Madison, Wisconsin, according to NIOSH 7303 and OSHA ID-125G.

Static bending

Conditioned samples (5.08-by 31.75-cm), four from each panel, were tested for MOE and MOR per ASTM standard D 1037-96a (ASTM 1998). Moisture content, nominal thickness, and specific gravity were determined for each specimen.

Internal bond strength

Tensile strength perpendicular to the surface was determined for six 5.08-by 5.08-cm-square conditioned specimens per panel evaluated according to ASTM standard D 1037-96a (ASTM 1998). A continuous load of 10 mm/min was applied throughout the test.

Results and discussion

Remediated CCA-treated particles and flakes were fabricated into particleboard and flakeboard panels and compared to panels made from untreated material with a comparable geometry. The extent of metal removal following remediation is shown in **Figure 1**. Bacterial fermentation clearly increased the removal of all three CCA components and preferentially copper. Remediation of flaked material had not been previously evaluated.

Physical properties of the panels are shown in **Table 1**. Direct comparison of particleboard prepared with remediated material and untreated material showed statistically significant ($p = 0.05$) differences in static bending properties (18% reduction in MOE and 47 percent reduction in MOR) and a 37 percent reduction in IB strength perpendicular to the surface. Average IB strength values for remediated particleboard panels, however, were higher than the ANSI minimum value of 0.45 N/mm² for M-2 grade medium-density particleboard (NPA 1993). In a previous laboratory-scale study, 2 kg of remediated particles was also blended with 10 percent urea-formaldehyde, but this material was formed into fewer panels, resulting in a smaller number of specimens for analysis (Clausen et al. 2001). Press time in the previous study was based on a predetermined time to reach an internal temperature of 121°C. In the study reported here, press time was computer-controlled and based on press platen temperature, resulting in more consistent results from panel to panel. In this study, results representing the larger sample size ($n = 16$) demonstrated greater variation in average stiffness and strength between remediated and untreated material (**Fig. 2**).

Although MOE and MOR of individual flakeboard specimens varied considerably (**Fig. 2**), the average values for all

Table 1. – Physical properties, static bending properties, and internal bond strength of particleboard and flakeboard panels from untreated or remediated southern yellow pine.^a

| Panel type | Thickness | | Moisture content | Specific gavity | Strength and stiffness | | |
|-------------------------|-----------|------|------------------|-----------------|------------------------|------------------------------------|-------------|
| | | | | | MOE | MOR | IBstrength |
| | (cm) | (in) | | | (%) | ----- (N · mm ²) ----- | |
| Particleboard | | | | | | | |
| Untreated ^b | 1.13 | 0.44 | 12.4 (0.15) | 0.58 (0.04) | 1,014 (89.63) | 6.48 (0.60) | 1.02 (0.07) |
| Remediated ^b | 1.11 | 0.44 | 12.1 (0.11) | 0.57 (0.04) | 827 (110.32) | 3.37 (0.60) | 0.64 (0.10) |
| Flakeboard | | | | | | | |
| Untreated ^b | 1.11 | 0.44 | 10.2 (0.31) | 0.67 (0.06) | 4,744 (372.32) | 31.82 (2.18) | 0.61 (0.07) |
| Remediated ^c | 1.10 | 0.43 | 10.4(0.31) | 0.63 (0.07) | 4,661 (275.79) | 31.26 (2.01) | 0.71 (0.01) |

^aMOE = modulus of elasticity; MOR = modulus of rupture; IB = internal bond. Values in parentheses are standard errors.

^b $n = 4$ panels, 16 specimens.

^c $n = 2$ panels, 8 specimens.

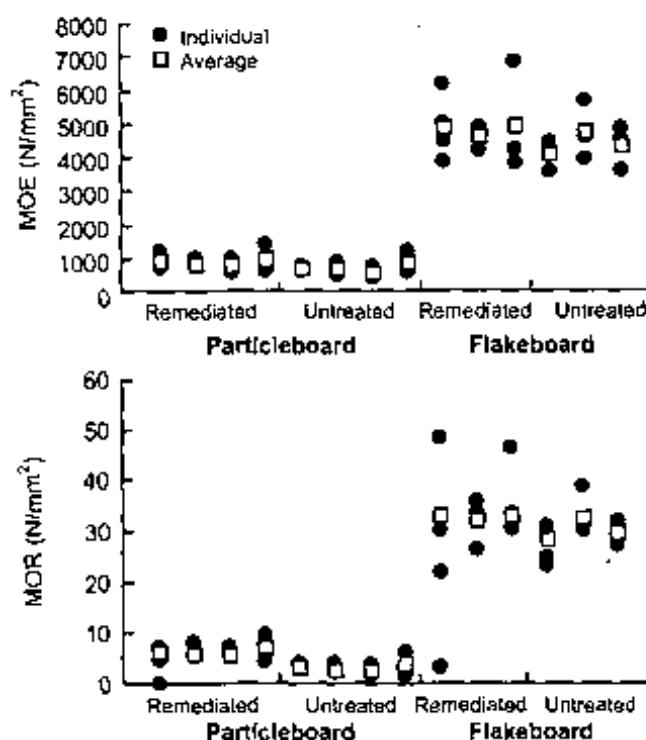


Figure 2. – Strength properties of particleboard and flakeboard panels.

remediated flakeboard specimens were statistically insignificant ($p = 0.05$) and varied less than 2 percent from the average values for control flakeboard specimens (1.7% and 1.8% reduction in MOE and MOR, respectively). Remediated flakeboard specimens had a 16 percent increase in IB strength compared to untreated flakeboard. Flaked material had not been remediated in previous laboratory-scale studies. However, average MOR values for remediated flakeboard exceeded the average values for sheathing grade oriented strandboard (OSB), and average MOE values were in the acceptable range of standard values for sheathing grade OSB (FPL 1999). Remediation removed 83 percent Cu, 86 percent Cr, and 95 percent As, presumably as a result of the high surface area accessible for acid extraction and bioleaching. Since metals are known to interfere with bonding of composites, greater metal removal in the flaked material may have accounted for better resin adhesion. Free metals are known to catalyze curing re-

actions and reduce wood penetration; free metals were washed from remediated material, thereby eliminating possible interference with IB strength.

Air samples were collected during panel pressing to determine if elemental arsine vapors were given off from the residual arsenic in the remediated particles or flakes. Results of ICP analysis were lower than the limit of detection; that is, <0.0017 mg/m³ or <0.50 µg/sample during particleboard pressing and <0.0026 mg/m³ or <0.50 µg/sample during flakeboard pressing. The reporting limit is 1.25 µg/sample. These results suggest that wood remediated by any process that reduces the arsenic level to 0.30 mg/g will not form unacceptable levels of elemental arsenic vapor during panel pressing.

Conclusions

Flaked CCA-treated remediated wood, from which 83 percent Cu, 86 percent Cr, and 95 percent As had been removed, was reassembled into flakeboard with 5 percent phenol-formaldehyde resin. Remediated flakeboard showed virtually no reduction in MOE and MOR compared to control panels made from untreated material. Not only was flaked material more readily remediated, but differences in flakeboard panel static bending and IB strength properties were insignificant from those of comparable panels made with untreated material.

Particulate CCA-treated remediated wood, from which 80 percent Cu, 71 percent Cr, and 89 percent As had been removed, was reassembled into particleboard with 10 percent urea-formaldehyde resin. Remediated particleboard panels showed an 18 percent reduction in MOE, 47 percent reduction in MOR, and 37 percent reduction in IB strength compared to comparable panels made from untreated material. Particulate material had lower levels of metal removed during remediation, which may partially account for the substantial reduction in static bending and tensile strength compared to that of control particleboard panels.

Inductively coupled plasma analysis of air samples taken during the pressing process showed that evolution of elemental arsenic vapors from residual arsenic (0.30 mg/g) in the remediated material was below the 1.25 µg/sample limit of detection by this method of analysis.

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